

# Baryon asymmetry from primordial black holes

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## Abstract

We propose a new scenario of the baryogenesis from primordial black holes (PBH). Assuming presence of microscopic baryon (or lepton) number violation and a CP violating operator such as  $\partial_\alpha F(\mathcal{R}...)J^\alpha$ , where  $F(\mathcal{R}...)$  is a scalar function of the Riemann tensor, time evolution of an evaporating black hole generates baryonic (leptonic) chemical potential at the horizon; consequently PBH emanates asymmetric Hawking radiation between baryons (leptons) and anti-baryons (leptons). Though the operator is higher dimensional and largely suppressed by a high mass scale  $M_*$ , we show that sufficient amount of asymmetry can be generated for a wide range of parameters of the PBH mass  $M_{\text{PBH}}$ , its abundance  $\Omega_{\text{PBH}}$ , and the scale  $M_*$ .

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# 1 Introduction

The standard model of particle physics is completed by the discovery of the Higgs boson, and is surprisingly consistent with the experimental data up to 1 TeV scale. However, there still remain several unsolved questions, e.g., What is the dark matter in the universe? Why are baryons more abundant than anti-baryons?

In order to answer these questions, gravitational effects might play important roles. One of the interesting possibilities of gravitational effects will be primordial black holes (PBH) [1, 2], which may be created in the early universe. PBHs could be formulated in the early universe by various processes such as large density fluctuations by inflation [3], preheating [4], in particular the tachyonic preheating [5], or bubble collisions [6] associated with first order phase transitions in the universe [7].<sup>1</sup> A PBH evaporates by Hawking radiation until the present time if its mass  $M$  is lighter than  $M = 10^{15}$ g. Consequently the abundance of the PBHs around  $M = 10^{15}$  g is strongly constrained by observations of the cosmic gamma ray [10, 11]. If the mass is between  $10^9$  g and  $10^{13}$  g, the Hawking radiation from the PBHs affect the big bang nucleosynthesis (BBN) and the abundance in this mass region is also strongly constrained (see e.g. [12]). PBHs with larger mass also play various important roles in cosmology. It may contribute to the dark matter in the universe for  $M \gtrsim 10^{15}$ g although its abundance is severely constrained [13, 14]. PBH may also explain the origin of the BHs with mass  $M = \mathcal{O}(10^{30})$ g [15, 16], whose binary mergers are observed in the recent detections of the gravitational waves by LIGO [17].

On the other hand, PBHs with smaller mass  $M < 10^8$  g will play a different role. One of the important roles of lighter PBHs will be to give a stage for generating baryon asymmetry. Hawking [18], Carr [19] and Barrow [20] proposed a scenario of Baryogenesis in which GUT scale particle/right handed neutrino are created by the Hawking radiation and then decay in a C and CP violating manner (see also [21, 22, 23, 24]). Recently Hook proposed a different scenario of Baryogenesis by using asymmetric Hawking radiation due to a dynamically generated baryonic chemical potential at the horizon [25]. There the CP violating interaction of the baryonic (or leptonic) current  $J^\alpha$  and the scalar curvature  $\mathcal{R}$

$$\frac{1}{M_*^2} \partial_\alpha \mathcal{R} J^\alpha, \quad (1)$$

is assumed, and the time evolution of the universe is used to generate the chemical potential  $\mu = \dot{\mathcal{R}}/M_*^2$  for baryons. The same interaction is used in the gravitational baryogenesis [26]. Indeed, the mechanism [25] essentially utilizes

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<sup>1</sup> See also Ref. [8] for discussion on PBH formation within the recently proposed framework of graviton condensates [9].

the idea of the spontaneous baryogenesis [27, 28] and gravitational baryogenesis [26] scenarios.

In this paper, we propose a new mechanism of the baryogenesis from evaporating PBHs. The mechanism is similar to that of [25], but instead of using the time evolution of the universe, we make use of the time evolution of the mass of the PBH itself for generating the Baryonic chemical potential  $\mu^2$ . This leads to a big difference between our mechanism and [25]. Since the scalar curvature around the PBH in vacuum is vanishing, we need to use higher dimensional operators such as

$$\frac{1}{M_*^4} \partial_\alpha (\mathcal{R}_{\mu\nu\rho\sigma} \mathcal{R}^{\mu\nu\rho\sigma}) J^\alpha, \quad (2)$$

where  $\mathcal{R}_{\mu\nu\rho\sigma}$  is the Riemann tensor. The operator is largely suppressed by the scale  $M_*$  and seems to be negligible but we show that it is sufficient to generate the desired asymmetry. It is due to the fact that the dynamically generated chemical potential  $\mu$ , as well as the temperature of the Hawking radiation  $T_H$ , is time-dependent through the mass of the BH. Indeed  $\mu/T_H$  is increasing as the PBH evaporates and becomes larger than 1 at the late stage of the evaporation. Consequently the asymmetry in the Hawking radiation becomes maximal after the PBH mass becomes smaller than a critical mass. The critical mass is determined by the scale  $M_*$ .

Once the chemical potential is generated at the horizon, Hawking radiation produces lepton/baryon asymmetry. Violation of lepton/baryon number in the underlining microscopic theory is necessary to induce the interaction (2), such as the interaction with the right-handed neutrinos or some effects related to the quantum gravity [30]. Since the sphaleron process [31, 32, 33] violates  $B + L$ , it is necessary to generate  $B - L$  if the typical Hawking temperature is higher than 100 GeV. The CP symmetry is broken by the effective operator (2). The time dependence of the PBH mass due to Hawking radiation induces time dependent and position dependent chemical potential, which is apparently a non-equilibrium process. In this way, Sakharov's three conditions are satisfied [34].

The paper is organized as follows. In the next section, we explain the basic mechanism of the scenario, and estimate the order of the asymmetry. We show that in some region of the parameter space of the PBH mass  $M_{\text{PBH}}$  and the scale  $M_*$ , the desired asymmetry  $n_B/s \simeq 8.7 \times 10^{-11}$  [35] can be generated. In Sec. 3, we discuss a possible origin of the higher dimensional operator (2), and estimate the order of the suppression scale  $M_*$ . In Sec. 4 we show that washout of the generated lepton number outside the horizon does not occur for the typical interaction discussed in Sec. 3. Sec. 5 is devoted to the summary and discussions.

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<sup>2</sup>A similar idea is proposed in [29].

## 2 Baryo (lepto)-genesis at the BH horizon

### 2.1 CP-violating interactions

The scenario of the gravitational baryogenesis [26] assumes the CP-violating interaction (1) where  $M_*$  is the cutoff scale of the effective theory. In an expanding universe, the time derivative of the scalar curvature  $\dot{\mathcal{R}}$  is non-zero and the interaction generates a chemical potential  $\mu = \dot{\mathcal{R}}/M_*^2$ . If a B-violating interaction is present and in thermal equilibrium, the distribution becomes asymmetric between baryons and anti-baryons. Then once the temperature drops below the freezing-out temperature of the B-violating interaction, the asymmetry remains in the later universe. The scenario is applied to the evaporating BH by the Hawking radiation [25]. The chemical potential is similarly generated by the evolution of the universe, but the freezing-out scenario is different. Since the thermal radiation from black holes is created, not by thermal process of B-violating interaction, but by genuine quantum process, the condition of the thermal equilibrium and the freezing-out in [26] is not necessary to be introduced.

In this section, we generalize the idea of the gravitational baryogenesis from a PBH [25] by taking the direct effect of the decay of the PBH mass  $M(t)$ . Since the scalar curvature  $\mathcal{R}$  vanishes outside of the BH in vacuum<sup>3</sup>, we consider an operator such as in (2). More generally, we can consider a class of higher dimensional operators<sup>4</sup>,

$$\frac{a_n}{M_*^{4n}} \partial_\alpha (\mathcal{R}_{\mu\nu\rho\sigma} \mathcal{R}^{\mu\nu\rho\sigma})^n J^\alpha. \quad n \geq 2. \quad (3)$$

It can be further generalized to

$$\partial_\alpha F(\mathcal{R}....) J^\alpha \quad (4)$$

where  $F(\mathcal{R}....)$  is any scalar function made of the curvature tensors. For the square of the Riemann curvature of the Schwartzschild BH is given by

$$\mathcal{R}_{\mu\nu\rho\sigma} \mathcal{R}^{\mu\nu\rho\sigma} = \frac{3M^2}{4\pi^2 M_P^4 r^6}, \quad (5)$$

a non-vanishing chemical potential  $\mu = a_n \partial_0 (\mathcal{R}_{\mu\nu\rho\sigma} \mathcal{R}^{\mu\nu\rho\sigma})^n / M_*^{4n}$  is generated if the BH mass  $M$  is decaying. Note that the chemical potential is dependent on time through  $M(t)$ . It also changes with the distance from the BH  $r$ . Since

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<sup>3</sup>In [26] and [25], the radiation dominated universe with the trace anomaly of the energy momentum tensor is studied so as to make  $\mathcal{R}$  non-vanishing.

<sup>4</sup> In addition to the CP-violating interaction, we implicitly assume that the existence of B-violating operator since otherwise this term vanishes by performing an integration by parts. See Sec. 3 and App. A for the discussion of the physical meaning of this operator.

the Hawking radiation is generated by the Bogoliubov transformation between the vacua of quantum fields near the horizon and at the far-infinity from the BH, the chemical potential at the horizon is relevant to generate the asymmetry of the Hawking radiation. The propagations of baryon and anti-baryon become different in the vicinity of the horizon, which shift the energy between them. Accordingly the generated asymmetry is proportional to the chemical potential evaluated at the horizon  $r = r_H$ .

## 2.2 Basic properties of evaporating BH

We summarize some basic facts about an evaporating BH. For simplicity<sup>5</sup> we consider the Schwarzschild black hole with the metric,

$$ds^2 = \left(1 - \frac{2GM}{r}\right) dt^2 - \frac{1}{\left(1 - \frac{2GM}{r}\right)} dr^2 - r^2 d\theta^2 - r^2 \sin^2 \theta d\varphi^2, \quad (6)$$

where  $G$  is the Newton constant, and  $M$  is the mass of the black hole. The radius of the horizon and Hawking temperature are given by

$$\begin{aligned} r_H &= 2GM = \frac{M}{4\pi M_P^2}, \\ T_H &= \frac{M_P^2}{M} \end{aligned} \quad (7)$$

where we have introduced the reduced Planck scale,

$$M_P := (8\pi G)^{-1/2} = 2.43 \times 10^{18} \text{ GeV} = 4.3 \times 10^{-6} g = (2.7 \times 10^{-43} s)^{-1}. \quad (8)$$

Though the Hawking radiation, particles are emitted [39] from the BH with the rate

$$\begin{aligned} \frac{dN}{d\omega dt} &= \frac{1}{2\pi} \frac{\Gamma}{e^{\omega/T_H} \pm 1}, \\ \frac{dE}{d\omega dt} &= \frac{1}{2\pi} \frac{\Gamma\omega}{e^{\omega/T_H} \pm 1}, \end{aligned} \quad (9)$$

where  $N, E$  are number and energy of emitted particles,  $\omega$  is the frequency, and  $\Gamma$  is the absorption probability (or gray body factor), which is caused by gravitational scatterings of emitted particles outside the horizon. The absorption probability depends on particle species, especially on the spin of the emitted particles. At low frequency,  $\omega \rightarrow 0$ , the absorption cross sections  $\sigma := \pi\omega^{-2}\Gamma$

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<sup>5</sup>In general, BH can have charge and angular momentum, but these would be quickly lost before most of BH mass disappears [36, 37, 38].

of spin 0 and 1/2 particles are constant while those of spin 1 and 2 particles are proportional to square and fourth power of frequency, respectively:

$$\sigma \rightarrow \begin{cases} \text{const.} & \text{for spin 0 and 1/2,} \\ \omega^2 & \text{for spin 1,} \\ \omega^4 & \text{for spin 2.} \end{cases} \quad (10)$$

As a result, most of the energy emitted from the PBH is carried by scalars and fermions [40].

We emphasize that the spectrum of the Hawking radiation is (almost) thermal, not because thermal plasma at temperature  $T_H$  is realized due to sufficiently fast interactions between emitted particles, but simply because the quantum vacuum at the horizon behaves as if it is in the thermal equilibrium for an observer at the far-infinity. In fact, even extremely weakly coupled particles (such as gravitons), that can be thermalized only at  $T_H \gtrsim M_P$ , are emitted according to the Hawking thermal spectrum.

Once we take into account the Hawking radiation, the spacetime is no longer stationary, and the metric (6) is no longer appropriate to describe the evaporating BH. Since the mass in (6) is the ADM mass which includes the energy of the emitted radiation it cannot correctly describe the mass of a decaying BH itself. A simplest alternative is the outgoing Vaidya metric [41], which is a solution of the Einstein equation describing outgoing null dust:

$$ds^2 = \left(1 - \frac{2GM(u)}{r}\right) du^2 + 2dudr - r^2 d\theta^2 - r^2 \sin^2 \theta d\varphi^2, \quad (11)$$

where  $u = t - r_*$ ,  $r_* = r + 2M \log |(r - 2M)/2M|$ . The apparent horizon is located at  $r = r_H = 2GM(u)$ . The corresponding energy momentum tensor is given by

$$T_{\mu\nu} = -\frac{dM}{du} \frac{1}{4\pi r^2} l_\mu l_\nu, \quad l_\mu = \partial_\mu u, \quad (12)$$

which describes dust with energy density  $\rho = (-dM/du)/(4\pi r^2)$  moving with a four-velocity  $l^\mu$ . The mass  $M(u)$  represents the Bondi mass, which is nothing but the mass of the BH itself. In the following, we consider the time-evolution of the Bondi mass  $\partial_u M(u)$ .

Because of the (almost) thermal Hawking radiation, the black hole loses its energy following

$$\frac{dM}{du} \simeq -(8\pi)^2 \frac{M_P^4}{M^2} \alpha, \quad (13)$$

where  $\alpha$  is a numerical coefficient [40] which can be determined by taking the effects of absorption cross section  $\sigma$ . As we discussed above, the dominant contribution to  $\alpha$  in the standard model comes from fermions. In Ref. [40], it is shown that the contribution to  $\alpha$  from  $\nu_e$  and  $\nu_\mu$  is  $1.575 \times 10^{-4}$ . Then, summing up all the fermionic degrees of freedom in the standard model, we obtain

$$\begin{aligned}\alpha &= 1.575 \times 10^{-4} \times \frac{3}{2} \times (1 + 2 + 4 \times 3) \\ &= 3.5 \times 10^{-3}.\end{aligned}\tag{14}$$

Solving the Eq. (13), the time dependence of  $M$  is given by

$$M(u) = M_{\text{PBH}} \left( 1 - \frac{u - u_{\text{ini}}}{\tau} \right)^{1/3},\tag{15}$$

and the lifetime of the black hole  $\tau$  becomes

$$\tau = \frac{M_{\text{PBH}}^3}{M_P^4} \frac{1}{3(8\pi)^2 \alpha}.\tag{16}$$

Here we take  $M = M_{\text{PBH}}$  at the initial time  $u = u_{\text{ini}}$ . From Eq. (15), we can see that the PBH completely evaporates until today if  $M_{\text{PBH}}$  is smaller than  $10^{20} M_P \sim 10^{15} g$ .

### 2.3 Dynamically generated chemical potential

Since the square of the Riemann tensor outside a PBH is

$$\mathcal{R}_{\mu\nu\rho\sigma} \mathcal{R}^{\mu\nu\rho\sigma} = \frac{12r_H^2}{r^6} = \frac{3M(u)^2}{4\pi^2 M_P^4 r^6},\tag{17}$$

we have a chemical potential  $\mu$ , if the CP-violating interaction Eq. (2) is present,

$$\mu = \frac{3}{2\pi^2} \frac{M}{M_P^4 M_*^4 r^6} \frac{dM}{du} \simeq -96\alpha \frac{1}{M M_*^4 r^6}.\tag{18}$$

By taking  $r = r_H$ , the chemical potential evaluated at the horizon becomes

$$\mu|_{r=r_H} = -\frac{3}{2}(8\pi)^6 \alpha M_P \left( \frac{M_P}{M} \right)^7 \left( \frac{M_P}{M_*} \right)^4.\tag{19}$$

Then the ratio of  $\mu|_{r_H}$  to the Hawking temperature is  $T_H = M_P^2/M$  is given by

$$\frac{\mu|_{r_H}}{T_H} = -\frac{3}{2}(8\pi)^6 \alpha \left( \frac{M_P}{M} \right)^6 \left( \frac{M_P}{M_*} \right)^4 = -\left( \frac{M_{\text{cr}}}{M} \right)^6,\tag{20}$$

where we have defined the critical mass  $M_{\text{cr}}$  by

$$M_{\text{cr}} = 8\pi M_P \left(\frac{3\alpha}{2}\right)^{1/6} \left(\frac{M_P}{M_*}\right)^{2/3} \sim 10 \times \left(\frac{M_P}{M_*}\right)^{2/3} M_P. \quad (21)$$

Note that the (absolute value of the) ratio is increasing as the BH mass  $M$  decreases. For  $M < M_{\text{cr}}$ , the ratio exceeds 1 and the asymmetry of the radiation becomes maximal. It indicates that if the initial mass of the PBH is smaller than the critical mass, only baryons are emitted <sup>6</sup>.

Parametrizing the scale  $M_*$  as  $M_* = 10^x M_P$  and the initial mass of the PBH as  $M_{\text{PBH}} = 10^y M_P$ , the condition of  $M_{\text{PBH}} = M_{\text{cr}}$  becomes

$$y = 1 - \frac{2}{3}x. \quad (22)$$

We will see later that the relation plays an important role in generating the asymmetry.

## 2.4 Leptogenesis from a PBH

Now let us explicitly calculate the asymmetry produced by the evaporation of *one* PBH. Since we have in mind a model in which the CP-violating interaction is induced by the interactions with the right-handed neutrinos, we hereafter suppose that the chemical potential induced at the horizon is the leptonic one. Then, as we see that the temperature of the universe at the epoch of evaporation is much higher than the electroweak scale, sphaleron processes transmute the generated leptons into baryons.

First note that the averaged energy per each emitted massless particle is

$$\langle E \rangle = \frac{\int d^3k \, k (e^{k/T_H} + 1)^{-1}}{\int d^3k (e^{k/T_H} + 1)^{-1}} = \frac{7\pi^4}{180\zeta(3)} T_H. \quad (23)$$

Inclusion of the chemical potential does not modify this much, so we use the value of the averaged energy in the following. By using this, the lepton number asymmetry can be estimated by the formula

$$\delta N_L = r_L A(M_{\text{PBH}}), \quad (24)$$

where  $r_L$  is the ratio of the number of leptons to the total number of fermions and scalars. In the standard model,  $r_L \simeq 1/5$ .  $A(M_{\text{PBH}})$  describes the lepton number excess as a function of the initial PBH mass (in the case that all emitted particles are leptons) and is given by

$$A(M_{\text{PBH}}) := - \int_{M_{\text{PBH}}}^0 \frac{dM}{\langle E \rangle} \frac{\int d^3k (e^{(k+\mu)/T_H} + 1)^{-1} - \int d^3k (e^{(k-\mu)/T_H} + 1)^{-1}}{\int d^3k (e^{(k+\mu)/T_H} + 1)^{-1} + \int d^3k (e^{(k-\mu)/T_H} + 1)^{-1}}. \quad (25)$$

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<sup>6</sup>Of course, particles without the baryon number are also emitted.



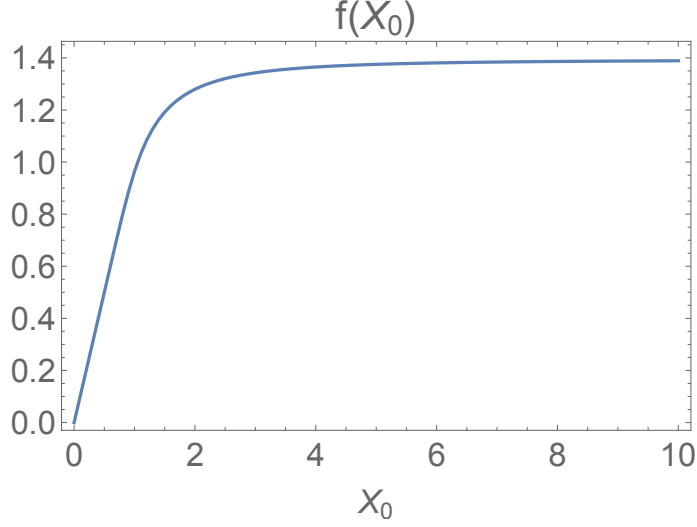


Figure 1: The function  $f(X_0)$  is plotted. The generated lepton number is proportional to  $f(X_0)$  where  $X_0 = (M_{\text{PBH}}/M_{\text{cr}})^2$ . Hence no lepton number is generated when the mass of the BH  $M$  is much larger than the critical mass  $M_{\text{cr}}$ .

The integral over the momenta  $k$  is proportional to the polylogarithmic function  $\text{Li}_3(z)$  defined by  $\text{Li}_3(z) := \sum_{k=1}^{\infty} z^k/k^3$ ;

$$\int \frac{d^3k}{e^{(k+\mu)/T_H} + 1} \propto \text{Li}_3(-e^{-\mu/T_H}). \quad (26)$$

Then changing the integration variable in (25) from  $M$  to  $X = (M/M_{\text{cr}})^2$ ,  $A(M_{\text{PBH}})$  becomes

$$A(M_{\text{PBH}}) = \frac{90\zeta(3)}{7\pi^4} \left( \frac{M_{\text{cr}}}{M_P} \right)^2 f(X_0) \quad (27)$$

where  $X_0 = (M_{\text{PBH}}/M_{\text{cr}})^2$  and the function  $f(X_0)$  is defined by

$$f(X_0) = \int_0^{X_0} dX \left( \frac{\text{Li}_3(-e^{1/X^3}) - \text{Li}_3(-e^{-1/X^3})}{\text{Li}_3(-e^{1/X^3}) + \text{Li}_3(-e^{-1/X^3})} \right). \quad (28)$$

The function  $f(X_0)$  is numerically depicted in Fig. 1. One can see that it is approximated by a linear function  $f(X_0) \simeq X_0$  for  $X_0 \lesssim 1$  and saturates  $f(X_0 \gtrsim 2) \sim 1.3$  for  $X_0 > 2$ . This means that the dominant lepton number asymmetry is produced when the BH mass is smaller than the critical mass. The saturation of  $f(X_0)$  for large values of  $X_0$  mean that when the BH mass is larger than  $M_{\text{cr}}$ , the radiation is almost symmetric and never contributes to the lepton number. On the other hand, the constant increase of  $f(X_0)$  below

$X_0 \sim 1$  means that the Hawking radiation from BHs with  $M < M_{\text{cr}}$  constantly contributes to the lepton number. The generated lepton number asymmetry from a single PBH is thus given by

$$\delta N_L = N_L - N_{\bar{L}} = r_L \frac{90\zeta(3)}{7\pi^4} \left( \frac{M_{\text{cr}}}{M_P} \right)^2 f(X_0) \sim 115 r_L \alpha^{1/3} \left( \frac{M_P}{M_*} \right)^{4/3} f(X_0), \quad (29)$$

where  $N_L$  and  $N_{\bar{L}}$  are the generated lepton and anti-lepton numbers, respectively. The lepton number asymmetry is given by  $\delta N_L/N = f(X_0)/X_0$  where  $N = N_L + N_{\bar{L}}$ . In order to generate the efficient asymmetry, the initial PBH mass must be comparable to or smaller than the critical mass  $M_{\text{cr}}$  determined by the scale  $M_*$  of the CP-violating operator. In the left panel of Fig. 2, we plot  $M_{\text{cr}}$  as a function of  $M_*$ . It increases as  $M_*$  decreases, and hence the smaller  $M_*$  is better for the large asymmetry generation. In the blue region, we cannot trust the effective field theory because  $T_H(M_{\text{cr}}) = M_P^2/M_{\text{cr}}$  becomes larger than  $M_*$ .

## 2.5 Lepton asymmetry in the universe

Let us briefly explain the cosmological history of the light PBHs. When the density perturbation becomes as large as the order one  $\delta\rho/\rho \sim 1$ , the PBH can be formed. The mass of PBH is determined by the energy within the Hubble horizon, namely,

$$M_{\text{PBH}} \simeq 4\pi\gamma M_P^2 H_{\text{ini}}^{-1}. \quad (30)$$

where  $\gamma$  is a numerical factor depending on details of the gravitational collapse. For it is usually considered to be  $\gamma \lesssim 0.2$ , we take  $\gamma = 0.2$  for simplicity. Here  $H_{\text{ini}}$  is the Hubble parameter at the time of the PBH formation. After it is formed, it emanates the Hawking radiation and when the Hubble parameter becomes the inverse of the PBH lifetime,

$$H_{\text{eva}} \simeq \frac{M_P^4}{M_{\text{PBH}}^3} 3(8\pi)^2 \alpha, \quad (31)$$

the PBH evaporates completely. Thus the ratio of the Hubble parameters is given by

$$\frac{H_{\text{eva}}}{H_{\text{ini}}} = 48\pi\alpha\gamma^{-1} \left( \frac{M_P}{M_{\text{PBH}}} \right)^2 \quad (32)$$

If the universe continues to be in the radiation dominated phase, the Hubble parameter is related to the scale factor of the universe as  $H \propto a^{-2}$ . Then the

ratio of the scale factors  $a$  during the evaporation is given by

$$\left(\frac{a_{\text{eva}}}{a_{\text{ini}}}\right) = \sqrt{\frac{\gamma}{48\pi\alpha}} \left(\frac{M_{\text{PBH}}}{M_P}\right). \quad (33)$$

Since the energy density of the universe changes as

$$\rho(t) = \rho_{\text{rad}}(t_i) \left(\frac{a(t_i)}{a(t)}\right)^4 + \rho_{\text{PBH}}(t_i) \left(\frac{a(t_i)}{a(t)}\right)^3, \quad (34)$$

the ratio of the energy density of PBHs  $\rho_{\text{PBH}}$  to the total energy density of the universe  $\rho_{\text{rad}}$  increases as the universe expands. Of course, the evaporation transfers the energy from the PBH to the radiation component and the actual evolution is more complicated [42]. It is not further discussed in the present paper.

The temperature of radiation just after the PBH evaporation  $T_{\text{eva}}$  can be estimated from

$$H_{\text{eva}} \simeq \sqrt{\frac{\pi^2 g_*}{90}} \frac{T_{\text{eva}}^2}{M_P}. \quad (35)$$

Here  $g_*$  is the effective degrees of freedom. Then we have

$$T_{\text{eva}} \sim 1.1 \times 10^{11} \text{ GeV} \left(\frac{\alpha}{3.5 \times 10^{-3}}\right)^{1/2} \left(\frac{106.75}{g_*}\right)^{1/4} \left(\frac{10^5 M_P}{M_{\text{PBH}}}\right)^{3/2}. \quad (36)$$

Notice that the typical value of  $T_{\text{eva}}$  is much higher than the electroweak scale for  $M_{\text{PBH}} \lesssim 10^{11} M_P \sim 10^5 g$ , and the lepton asymmetry produced by the PBH evaporation can be converted into the baryon asymmetry by the sphaleron process.

We also note that the Hubble parameter  $H_{\text{ini}}$  must be smaller than the Hubble parameter during inflation  $H_{\text{inf}} \sim 10^{14} \sqrt{r/0.1} \text{ GeV}$ , where  $r$  is the tensor to scalar ratio. Thus we have the lower bound on the PBH

$$M_{\text{PBH}} \gtrsim \frac{4\pi\gamma M_P^2}{H_{\text{inf}}} \sim 6 \times 10^4 \sqrt{\frac{0.1}{r}} M_P. \quad (37)$$

Only PBHs satisfying the condition can be created in our universe.

Having the above cosmological history in mind, we can estimate the lepton asymmetry after the PBH evaporation,

$$\frac{n_L}{s} = \frac{n_{\text{PBH}}}{s} \delta N_L = \Omega_{\text{PBH}} \frac{\rho_{\text{rad}}}{s} \frac{\delta N_L}{M_{\text{PBH}}} \quad (38)$$

where  $\Omega_{\text{PBH}} = \rho_{\text{PBH}}/\rho_{\text{rad}}$  is the density ratio of the PBH to the radiation, which is evaluated at the epoch of evaporation. Using  $\rho_{\text{rad}}/s = 3T_{\text{eva}}/4$ , (29)

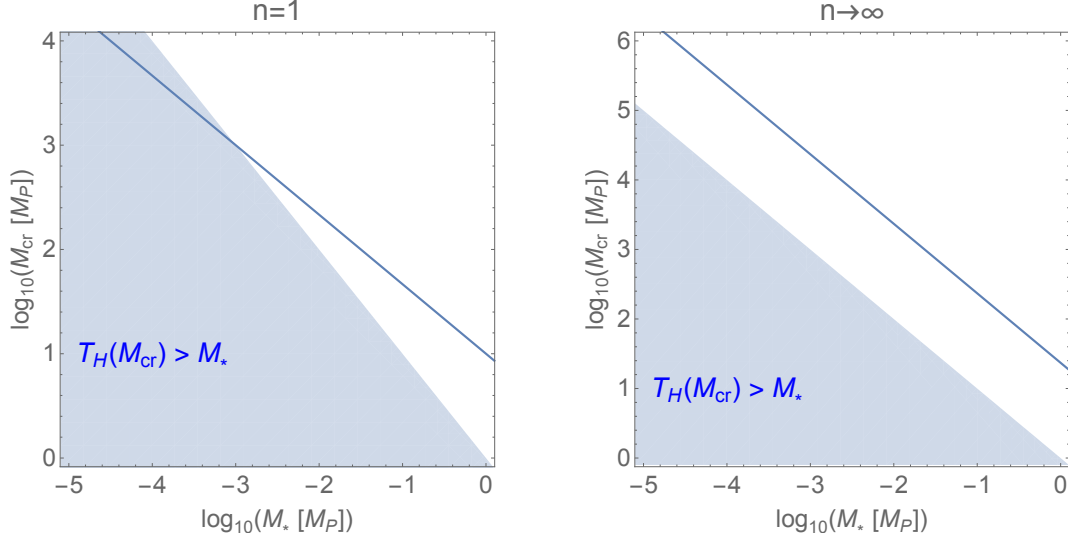


Figure 2: The critical mass of the PBH  $M_{\text{cr}}$  in (21) is plotted as a function of the scale  $M_*$ . The lepton asymmetry in Eq. (24) is generated when the PBH mass is lighter than  $M_{\text{cr}}$ . The effective field theory approach will not be valid in the shaded region where the Hawking temperature is larger than the suppression scale  $M_*$  of the higher dimensional operators. But note that this does not mean that the shaded region should be excluded. The right panel shows the critical mass in (41) for the chemical potential generated by more generalized operators. Here we assume  $a_n = 1/n$  and take  $n \rightarrow \infty$ .

and (36), we have

$$\begin{aligned} \frac{n_L}{s} \simeq & 5.3 \times 10^{-10} \left( \frac{r_L}{1/5} \right) \left( \frac{106.75}{g_*} \right)^{1/4} \left( \frac{\alpha}{3.5 \times 10^{-3}} \right)^{5/6} \\ & \times \Omega_{\text{PBH}} f(X_0) \left( \frac{10^5 M_P}{M_{\text{PBH}}} \right)^{5/2} \left( \frac{10^{-2} M_P}{M_*} \right)^{4/3}, \end{aligned} \quad (39)$$

which is conserved until now under the assumption that there is no entropy production.  $f(X_0) \sim 1.3$  if the initial mass of the PBH is larger than the critical mass  $M_{\text{cr}}$  defined in (21). The condition is satisfied for typical values of  $M_{\text{PBH}}$  and  $M_*$ . From this rough estimation, we can see that the observed amount of the asymmetry,  $n_L/s \sim 10^{-10}$ , can be successfully produced.

In the left panel of Fig. 3, we plot the lepton asymmetry generated in presence of the CP-violating interaction (2) for  $\Omega_{\text{PBH}} = 1$ . In order to generate the observed baryon asymmetry  $n_B/s \simeq 8.7 \times 10^{-11}$ , the mass of the PBH (the vertical axis) and the scale  $M_*$  suppressing the interaction must be on the line with  $10^{-10}$ . If the density ratio of PBHs is less than 1, i.e.,  $\Omega_{\text{PBH}} = 10^{-s}$  with  $s > 0$ , the parameters  $(M_{\text{PBH}}, M_*)$  must be on the line with a larger value  $10^{s-10}$ . Below the dotted line, the mass  $M_{\text{PBH}}$  is smaller than the critical mass

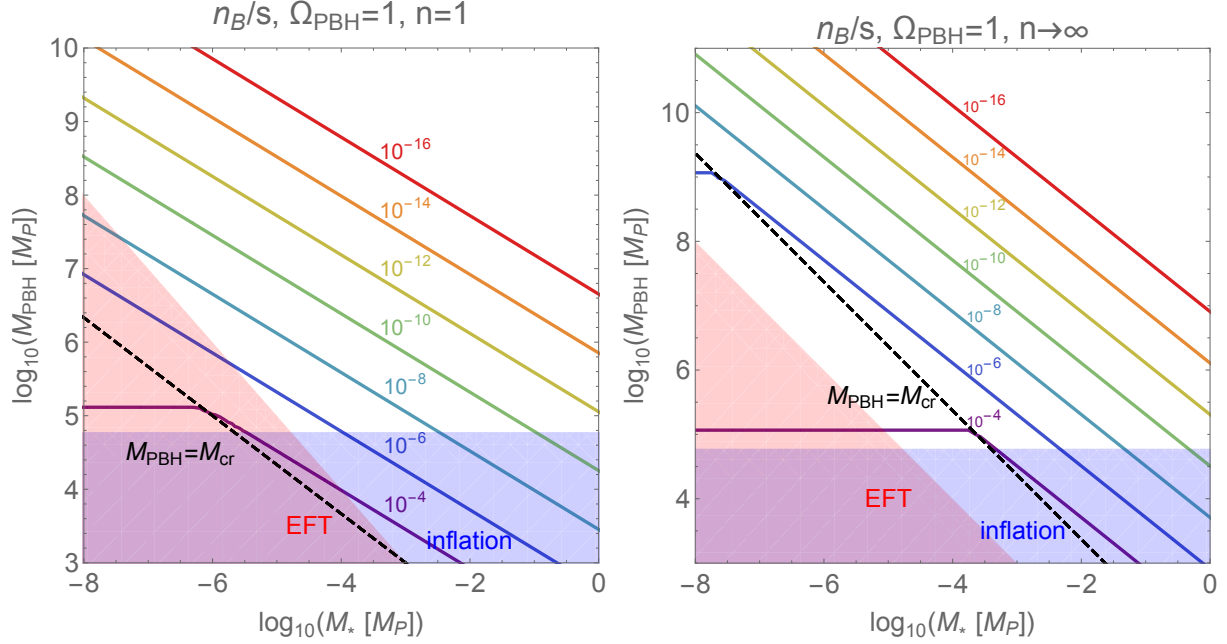


Figure 3: The contour plot of the lepton asymmetry produced by the evaporation of the PBH. The observed baryon asymmetry is  $n_B/s \simeq 8.7 \times 10^{-11}$ . The left panel shows the result (39) for  $\Omega_{\text{PBH}} = 1$ . The dotted line expresses the value of  $M_{\text{cr}}$ , and below the line the generated asymmetry is simply determined by the PBH mass  $M_{\text{PBH}}$ . A PBH with mass lower than  $M_{\text{PBH}} \sim 10^5 M_P$  is not created in our universe as discussed in (37). The orange region is the region where the effective field theory may not be valid since the Hawking temperature is higher than  $M_*$ . The graph shows that the baryogenesis from the PBH works as far as  $\Omega_{\text{PBH}} > 10^{-5}$ . The right panel shows the lepton asymmetry in the case of a more generalized CP-violating operator discussed in section 2.6. We use Eq. (46) with  $a_n = 1/n, r_L = 1/5$  and  $\Omega_{\text{PBH}} = 1$ . In this case, more asymmetry is efficiently generated compared to the  $n = 1$  case in the left panel, and the density ratio of PBH can be as low as  $\Omega_{\text{PBH}} = 10^{-6}$ .

$M_{\text{cr}}$  and the asymmetry is simply determined by the PBH mass  $M_{\text{PBH}}$ . The shaded region is not allowed because below  $M_{\text{PBH}} \sim 10^5$  g, PBH is not created in our universe (37). In the orange region the effective field theory may not be valid owing to  $T_H > M_*$ . Therefore, the graph shows that the baryogenesis from the PBH works as far as  $\Omega_{\text{PBH}} > 10^{-5}$ .

## 2.6 More general CP-violating interactions

So far we have studied the CP-violating interaction of (2). Next we consider more general higher dimensional operators introduced in Eq. (3). The calculation is the same as the simplest case discussed so far. The chemical potential is dynamically generated at the horizon and the ratio to the Hawking temperature is given by

$$\left. \frac{\mu}{T_H} \right|_{r=r_H} = - \left( \frac{M_{\text{cr}}}{M} \right)^{4n+2} \quad (40)$$

where the critical mass is given by

$$M_{\text{cr}} =: \sqrt{C_n} M_P, \quad C_n = (n a_n)^{1/(2n+1)} (128 \alpha \pi^2)^{1/(2n+1)} \left( 32 \sqrt{3} \pi^2 \right)^{2n/(2n+1)} \left( \frac{M_P}{M_*} \right)^{4n/(2n+1)}. \quad (41)$$

Notice that, compared to the  $n = 1$  case in (21), the exponent of  $(M_P/M_*)$  in  $\sqrt{C_n}$  is larger and accordingly the critical mass becomes larger. Parametrizing  $M_*$  as  $M_* = 10^x M_P$  and  $M_{\text{PBH}} = 10^y M_P$ , the condition of  $M_{\text{PBH}} = M_{\text{cr}}$  for  $n \rightarrow \infty$  with  $a_n = 1/n$  becomes

$$y = 1.37 - x. \quad (42)$$

In the right panel of Fig. 2, we plot the critical mass  $M_{\text{cr}}$  for  $n = \infty$  with  $a_n = 1/n$ . In the blue region, the Hawking temperature is higher than  $M_*$  and the effective theory description may not be valid.

By introducing the new integration variable  $X = (M/M_{\text{cr}})^2$  as before, we obtain the lepton number emitted from a single PBH as

$$\delta N_L = r_L \frac{90 \zeta(3)}{7 \pi^4} \left( \frac{M_{\text{cr}}}{M_P} \right)^2 f_n(X_0) \quad (43)$$

where

$$f_n(X_0) = \int_0^{X_0} dX \left( \frac{\text{Li}_3(-e^{-1/X^{2n+1}}) - \text{Li}_3(-e^{1/X^{2n+1}})}{\text{Li}_3(-e^{-1/X^{2n+1}}) + \text{Li}_3(-e^{1/X^{2n+1}})} \right). \quad (44)$$

The function  $f_n(X_0)$  behaves similarly to the previously defined function  $f(X_0) = f_1(X_0)$  but with a rapid change of behavior around  $X_0 = 1$ . In the large  $n$  limit,

$$\delta N_L = r_L \frac{90\zeta(3)}{7\pi^4} (na_n)^{1/2n} \left(32\sqrt{3}\pi^2\right) \left(\frac{M_P}{M_*}\right)^2 f_n(X_0). \quad (45)$$

Hence, for large  $n$ , the lepton asymmetry is found to be

$$\begin{aligned} \frac{n_L}{s} &\simeq 5.9 \times 10^{-8} \left(\frac{r_L}{1/5}\right) \left(\frac{106.75}{g_*}\right)^{1/4} \left(\frac{\alpha}{3.5 \times 10^{-3}}\right)^{1/2} \\ &\times \Omega_{\text{PBH}} f_n(X_0) \left(\frac{10^5 M_P}{M_{\text{PBH}}}\right)^{5/2} \left(\frac{10^{-2} M_P}{M_*}\right)^2 (na_n)^{1/2n}, \end{aligned} \quad (46)$$

According to the behavior of  $a_n$ , the asymptotic behavior of  $(na_n)^{1/2n}$  is given as

$$(na_n)^{\frac{1}{2n}} \rightarrow \begin{cases} 1 & \text{for } a_n \sim \frac{1}{n} \\ \sqrt{\frac{e}{n}} & \text{for } a_n \sim \frac{1}{n!} \sim n^{-n} e^n \end{cases}. \quad (47)$$

It is interesting to note that the higher dimensional operators are more efficient to produce larger amount of the asymmetry. If we take a sum of these operators,

$$\sum_n \frac{a_n}{M_*^{4n}} \partial_\alpha (\mathcal{R}_{\mu\nu\rho\sigma} \mathcal{R}^{\mu\nu\rho\sigma})^n J^\alpha, \quad (48)$$

the chemical potential is also summed  $\mu/T_H \rightarrow \sum_n \mu_n/T_H$ . Consequently the critical mass becomes larger and more asymmetry can be generated.

We now estimate the produced asymmetry created by the higher dimensional interactions, assuming  $(na_n)^{1/2n} \sim 1$ . In the right panel of Fig. 3, we plot the produced asymmetry  $n_L/s$  in Eq. (46) for  $\Omega_{\text{PBH}} = 1$  and  $r_L = 1/5$ . We can see that the observed asymmetry,  $n_B/s \simeq 8.7 \times 10^{-11}$ , is realized in a wide range of parameters as far as  $\Omega_{\text{PBH}} > 10^{-6}$ .

We note that, if the mass of the PBH is less than  $10^8 \text{g}$  [12], there are no observational constraints. Thus the mass region in which the present baryogenesis scenario works is all allowed. It is also interesting to note that the general interactions suppressed by  $M_*$  can generate larger baryon asymmetry. This does not mean that the last stage of the evaporation when the BH mass is of the order of the Planck mass, but it is due to the fact that the critical mass  $M_{\text{cr}}$  is larger for  $n > 2$ . The most lepton number is generated when the BH mass is near the critical mass. This also suggests that, if we sum up all higher dimensional operators, a larger value of chemical potential is generated at the horizon and accordingly more asymmetry can be produced. It is amusing to study the baryogenesis scenario from PBHs in a UV completion theory such as the string theory.

### 3 Possible origin of CP-violating operators

In this section, we discuss a possible origin of the CP-violating higher dimensional operators. In order to generate these operators, the underlying physics need to violate CP symmetry and the lepton number. One of the simplest possibility is the Majorana mass terms of the right handed neutrinos. As usual, imaginary phases of the mass matrix break the CP symmetry. The Lagrangian we consider is

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + y_N \bar{L} N_R \tilde{\Phi} + \frac{M_R}{2} \bar{N}_R^c N_{Ri} + \text{h.c.}, \quad (49)$$

where  $y_N$  is the neutrino Yukawa coupling, and  $M_N$  is the mass of the right handed neutrinos. Recently, McDonald and Shore [43, 44] explicitly calculated loop diagrams containing the above interactions coupled with the gravity in the external lines. They took the conformally flat metric,  $g_{\mu\nu} = (1 + h)\eta_{\mu\nu}$  where the field  $h$  is treated as a background field, and then calculated the two-loop Feynman diagrams in Fig. 5 to obtain the higher dimensional operator used in the gravitational leptogenesis,

$$\frac{1}{M_{MS}^2} \partial_\mu \mathcal{R} j^\mu. \quad (50)$$

Since the right handed neutrinos are integrated out, the mass scale of the higher dimensional interaction is essentially given by<sup>7</sup>

$$\frac{1}{M_{MS}^2} \sim \frac{1}{(16\pi^2)^2} \frac{\text{Im}((y_N y_N^\dagger)^2)}{M_N^2}. \quad (51)$$

The higher dimensional operators utilized in the present paper will also arise by calculating similar diagrams with more gravitons in the external lines. To prove it, we need to consider a more generic form of the metric and further involved calculations are necessary, so we leave it for future investigations. From dimensional and diagrammatic arguments, it can be expected that the mass scale  $M_*$  is given by

$$\frac{1}{M_*^4} \sim \frac{1}{(16\pi^2)^2} \frac{\text{Im}((y_N y_N^\dagger)^2)}{M_N^4}. \quad (52)$$

Let us now give a rough estimation for the scale  $M_*$  using this formula. The see-saw mechanism indicates that the typical order of  $M_N$  is given by  $M_N \sim (y_N v)^2 / m_\nu \sim y_N^2 10^{16} \text{ GeV}$ , where  $v \sim 100 \text{ GeV}$  and  $m_\nu \sim 10^{-3} \text{ eV}$ . The scale  $M_*$  is proportional to  $M_N$  but also dependent on the Yukawa coupling  $y_N$

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<sup>7</sup>These authors further claimed possible appearance of an enhancement factor depending on the mass hierarchy of the right handed neutrinos. We do not discuss such effects here.



and the CP-violating parameter  $\epsilon$ . If we take the Yukawa coupling as  $y_N \sim 1$ , smallness of  $\epsilon$  makes the scale  $M_*$  larger than  $10^{16}$  GeV. On the other hand, if we assume that  $y_N$  is as small as, e.g.  $y_N = 10^{-5}$  and the CP-violating parameter is of order 1, the scale  $M_*$  can be lowered to  $10^{11}$  GeV. Note that from recent arguments on the hierarchy problem of the electroweak scale, it is preferable to take the scale of the right-handed neutrinos relatively lower. Hence the scale  $M_*$  may be expected to take a value in the region,  $10^{-7}M_P < M_* < M_P$ .

We also emphasize that, other than the right handed neutrinos, if CP is broken in the UV theory including gravity, we can naturally expect appearance of the effective operators, Eq.(3). More detailed calculations and discussions are left for future studies.

## 4 Effect of washout outside the BH

If the CP-violating interaction such as Eq.(3) is present, decay of the PBH mass by Hawking radiation breaks time-reversal symmetry and generates chemical potential at the horizon. Then the radiation becomes asymmetric. As already mentioned before, the distribution looks thermal but it does not mean that the lepton number violating interaction is in the thermal equilibrium. The Hawking radiation is emitted because of the quantum mechanical effect, and reflects the fact that the quantum vacuum near the horizon is different from the Minkowski vacuum. In this respect, the mechanism of baryogenesis is very different from the gravitational baryogenesis [26], in which decoupling of the baryon number violating interaction is necessary to fix the final amount of asymmetry.

It is, however, necessary to check whether the generated asymmetry is washed out by the baryon (or lepton) number violating interactions outside of the black hole horizon. As discussed in the previous section, we assumed that the microscopic process violates the lepton number through the interaction with the right-handed neutrinos. By integrating out them, we have the following dimension-5 operator,

$$S_L = \int d^4x \left( \frac{1}{\Lambda} LLHH \right). \quad (53)$$

After the Higgs acquires the vev  $\langle H \rangle = v \simeq 246$  GeV, it gives the mass to the neutrinos. Hence  $\Lambda$  is determined to be

$$\Lambda \sim \frac{v^2}{m_\nu} \sim 2.5 \times 10^{-2} M_P, \quad (54)$$

where  $m_\nu$  is the neutrino mass and we put  $m_\nu = 10^{-3}$  eV.

The cross section is estimated by  $\sigma \sim 1/\Lambda^2$  at low energy scale. The particle number density is given by  $n \sim T_H^3$  near the horizon where the particles are

created. Then the scattering rate of the lepton number violating interaction at the horizon is given by

$$\Gamma_{\mathcal{L}}^0 = \sigma n = T_H^3 / \Lambda^2 \sim 1.6 \times 10^{-12} \left( \frac{10^5 M_P}{M} \right)^3 M_P. \quad (55)$$

But the rate is much slower than the typical time scale of the created particle to move away from the BH, namely  $\Gamma_{\mathcal{L}}^0 \ll r_H^{-1} = (M_P/M)M_P$  for the BH mass  $M > 10^5 M_P$ . Hence the particle density is quickly diluted by the factor  $(r_H/r)^2$ , where  $r$  is the distance from the BH, and the interaction rate is reduced to  $\Gamma_{\mathcal{L}} = \Gamma_{\mathcal{L}}^0 (r_H/r)^2$ . Since the Hubble parameter of the universe at the epoch of evaporation in (31) is estimated to be  $H_{\text{eva}} \sim 10^{-14} (10^5 M_P/M)^3 M_P$ , the dilution factor  $(r_H/r)^2$  instantly makes  $\Gamma_{\mathcal{L}}$  much smaller than  $H_{\text{eva}}$ . Hence the interaction is not in the chemical equilibrium at the time of evaporation with the Hubble  $H_{\text{eva}}$ .

Next we check the condition of washout when the particles are at higher energy than  $M_N$ . The infinite blue shift near the BH horizon enhances the energy of the particle by the factor  $(1 - r_H/r)^{-1/2}$ . Then, near the horizon, the cross section of lepton number violating interaction is replaced by its high energy counterpart  $\sigma \sim y_N^2/s \sim y_N^2(1 - r_H/r)/T_H^2$ . Taking the dilution factor  $(r_H/r)^2$  into account, we have

$$\Gamma_{\mathcal{L}} \sim y_N^2 T_H \frac{r_H^2}{r^2} \left(1 - \frac{r_H}{r}\right). \quad (56)$$

The maximal value of  $\Gamma_{\mathcal{L}}$  is obtained by

$$\Gamma_{\text{max}} \sim 0.15 y_N^2 T_H = 0.15 \frac{y_N^2}{4\pi r_H} \quad (57)$$

at the position  $r \sim 1.5 r_H$ . Again this is much smaller than  $r_H^{-1}$  by a factor  $10^{-2} y_N^2$ , and the emitted particles move away quickly from the BH, so the scattering rate is reduced to  $\Gamma_{\mathcal{L}} \sim (r_H/r)^2 \Gamma_{\text{max}}$ . Compared with the Hubble  $H_{\text{eva}}$  in (31), when the particle moves to  $r \sim 10^3 r_H$ ,  $\Gamma_{\mathcal{L}} < H_{\text{eva}}$  is satisfied. Hence, if  $y_N < 0.1$  the time that the particle moves to that position is sufficiently short for the lepton number violating interaction to occur, and the generated lepton number is never washed out.

## 5 Summary and discussions

In this paper, we have proposed a new scenario of baryogenesis from evaporating PBHs. The key element is the CP violating operator Eq. (2), which generates the splitting of energy spectrum between particles and anti-particles if the BH is decaying. The mechanism is similar in spirit to the gravitational baryogenesis

[26] or the mechanism by Hook [25] who applied the gravitational baryogenesis to the PBH, but an essential difference is that we make use of the time-evolution of the BH itself [29], not the cosmological evolution, to generate the chemical potential. Because of this, the ratio of the chemical potential to the Hawking temperature  $\mu/T_H$  becomes a function of the decaying mass of evaporating BHs and, when the mass becomes under the critical mass, the ratio  $|\mu/T_H|$  exceeds 1. After this epoch, maximal asymmetry can be generated. Due to such efficiency of generation mechanism, even though the CP-violating operator is largely suppressed by high energy scale  $M_*$ , we show that sufficient amount of baryon asymmetry  $n_B/s \simeq 8.7 \times 10^{-11}$  can be obtained in wide range of parameter space if the density ratio of PBHs at the epoch of evaporation is  $\Omega_{\text{PBH}} > 10^{-6}$ . If the scenario really explains the baryon asymmetry of the universe, it constrains model buildings beyond the standard model because the PBH can radiate heavy particles that may decay later, e.g. during the BBN. Thus the present scenario favors simpler model buildings such as [45].

The estimation of the generated asymmetry and the requirement for  $\Omega_{\text{PBH}}$  in the present paper will change if we take other effects into account. First, in our analysis we evaluated the chemical potential at the horizon  $r = r_H$ . There is, however, a discussion [46] [47] that the Hawking radiation originates in the longer-region  $r > r_H$ . If we evaluate  $\mu$  at  $r = cr_H$ , the chemical potential is reduced by  $c^{-6n}$  and the critical mass  $M_{\text{cr}}$  by  $c^{-6n/(4n+2)} \rightarrow c^{-3/2}$  (or increases the effective  $M_*$  by  $c^{3/2}$ ) for  $n \rightarrow \infty$ . Therefore it is not a big effect.

In the analysis we used the adiabatic approximation, namely we have implicitly assumed that the time scale characterizing the Hawking radiation is shorter than that of the change of mass of the PBH. Here we confirm the validity of this assumption. The typical time scale of Hawking radiation is estimated from the uncertainty relation between time and energy,

$$\Delta t \sim \frac{1}{\Delta E} \sim \frac{1}{T_H}. \quad (58)$$

The assumption of the adiabaticity is justified if the change of the PBH mass is negligibly small during  $\Delta t$ . Using Eq. (13), we have

$$\begin{aligned} \left| \frac{dM}{dt} \Delta t \right| &\simeq \frac{\pi N}{480} \frac{M_P^4}{M^2 T_H} \\ &= \frac{\pi N}{480} \left( \frac{M_P}{M} \right)^2 M \end{aligned} \quad (59)$$

which is much smaller than  $M$  for  $M \gg M_P$ . Therefore, we can safely treat the system adiabatically.

If PBHs are responsible for the baryon asymmetry in the universe, they can also be responsible for gravitational waves. PBHs emit gravitational waves either by Hawking radiation or by a formation of PBH binaries, but the Hawking

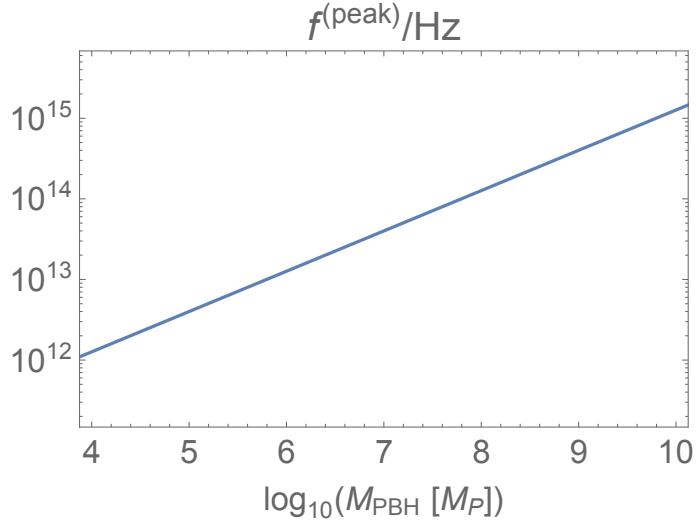


Figure 4: The peak frequency of gravitation wave from Hawking radiation from PBH as a function of  $M_{\text{PBH}}$ .

radiation would provide the strongest signal [48]. In Ref. [48], they estimated the peak frequency  $f^{(\text{peak})}$  and the peak amplitude  $h_0^2 \Omega_{\text{GW}}$  as

$$f^{(\text{peak})} = 4 \times 10^{12} \text{ Hz} \sqrt{\frac{M_{\text{PBH}}}{10^5 M_{\text{P}}}}, \quad h_0^2 \Omega_{\text{GW}} \sim 10^{-7}, \quad (60)$$

if PBH dominates the universe. Note that the peak amplitude does not depend on  $M_{\text{PBH}}$ . In Fig. 4, the peak frequency of the gravitational waves from the PBH is plotted as a function of its mass. It is amusing to consider a cosmological history in which PBHs dominate in the early universe. But the expected gravitational waves seem to be difficult to observe since its frequencies are too high for the near future experiments.

The final comment is the formation mechanism of the PBHs. There are various possibilities to create PBHs in the early universe as summarized in the introduction. The bubble collisions [6] associated with the first order phase transition in the universe [7] is becoming more interesting recently since the discovery of the Higgs boson and strong constraints on the TeV scale physics have stimulated reconsideration of our view of the cosmological history. In particular, revival of radiative symmetry breaking via the Coleman Weinberg mechanism [49, 50, 51] suggests that the phase transition will be a strong first order type. In such models, bubble collisions of the true vacua can generate strong gravitational waves [52], topological objects such as monopoles [53], or PBHs [6]. It is interesting to pursue further cosmological consequences of the strong first order phase transitions, in relation to the particles physics models beyond the SM.

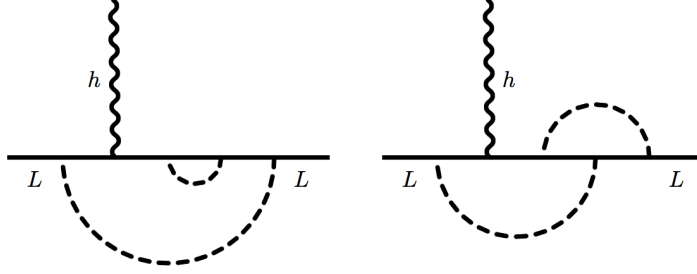


Figure 5: The diagrams inducing the effective operator Eq. (50) by integrating out the right handed neutrinos.  $L$  and  $h$  are the lepton doublet, and external gravitational field, respectively.

## A Is chemical potential physical?

If the (lepton number) current is conserved, the operator of the type in Eq. (4) seems to vanish by integrating by parts or by rotating the phase of leptons as  $\psi$  as  $\psi \rightarrow \exp(iF(\mathcal{R}...))\psi$ . It implies that the lepton number violation is necessary to justify the microscopic origin of such CP-violating effective operators. Indeed McDonald and Shore [44] obtained such a term by integrating the right-handed neutrinos whose interactions violate the CP and the lepton number conservation microscopically.

But it is still paradoxical why we are not allowed to do such phase rotation to remove the effect of lepton asymmetry. First note that if the interaction is replace by  $\mu J^0$  where  $\mu = \dot{F}$  is assumed to be a constant, the phase rotation becomes  $\psi \rightarrow \exp(i\mu t)\psi$ . This is nothing but the shift of the energy  $\omega \rightarrow \omega - \mu$  for leptons and  $\omega \rightarrow \omega + \mu$  anti-leptons. Since the vacuum state is defined so as to fill all negative energy levels, the phase rotations simply changes the definitions of the vacuum. Thus such phase rotation should be correlated with the definition of the vacuum state, and with the definition of the lepton number of the vacuum.

In the case we are discussing, the current is coupled to the total derivative  $\partial_\alpha F(\mathcal{R})$  and  $F(\mathcal{R})$  is a smooth function in the spacetime. Especially it vanishes at  $r = \infty$  and takes a nonvanishing value at the BH horizon  $r = r_H$ . Therefore, if we assume that  $F(\mathcal{R})$  is a slowly changing function in time and can be expanded as  $F(t, r) = F_0(r) + \mu(r)t + \dots$ , the phase rotation changes the energy levels of leptons  $\omega \rightarrow \omega - \mu(r)$  as a function of the position  $r$ . In this sense, the situation is similar to the discussion of chiral anomaly as the spectral flow in the Hamiltonian formulation. Now the question is that how we can define the vacuum of quantum field at  $r = \infty$  and  $r = r_H$  separately. And this is nothing but the issue of the Hawking radiation. At  $r = \infty$ ,  $F(\mathcal{R})$  vanishes and there is no ambiguity in defining the vacuum. At  $r = r_H$ , we first define the appropriate

vacuum state (such as the Unruh vacuum) so that an infalling observer does not encounter any divergences, and then calculate the effective action. Once the effective operator is induced as performed in [44, 43], then we can no longer shift the energy level (see also [54] and [55].) This is the reason why we should not rotate the basis after we calculate the effective interaction, and the CP-violating operator and the resulting chemical potential derived from Eq. (49) has a physical meaning.<sup>8</sup> It will be interesting to obtain the asymmetry in spectrum of the Hawking radiation without resorting to the calculation of the effective interaction, i.e. by explicitly calculating the lepton wave function in the eikonal approximation with the coupling to the right-handed neutrinos included. We want to come back to this problem in future. (See also Appendix B.)

## B Hawking radiation with a chemical potential

Here we briefly explain why the chemical potential modifies the spectrum of Hawking radiation. We start from the following action in the Schwarzschild black hole geometry.

$$\begin{aligned} S &= \int \sqrt{-g} d^4x \left( \bar{\psi} i \not{\partial} \psi + \frac{C}{M_*^4} g^{\mu\nu} \partial_\mu (\mathcal{R}_{\alpha\beta\gamma\delta} \mathcal{R}^{\alpha\beta\gamma\delta}) \bar{\psi} \not{\partial} \psi \right) \\ &= \int \sqrt{-g} d^4x \bar{\psi} \left( i \partial_\mu - \frac{C}{M_*^4} \partial_\mu (\mathcal{R}_{\alpha\beta\gamma\delta} \mathcal{R}^{\alpha\beta\gamma\delta}) \right) \gamma^\mu \psi. \end{aligned} \quad (61)$$

The action has the same form as

$$\int \sqrt{-g} d^4x \bar{\psi} (i \partial_\mu - e A_\mu) \gamma^\mu \psi, \quad (62)$$

by identifying  $C \partial_\mu (\mathcal{R}_{\alpha\beta\gamma\delta} \mathcal{R}^{\alpha\beta\gamma\delta}) / M_*^4$  with the gauge potential  $A_\mu$ . Thus the coupling to the background gravity is nothing but the pure gauge configuration (but it cannot be gauged away as discussed in the previous Appendix). It is now instructive to briefly sketch the derivation of Hawking radiation in the case of the charged black hole following Refs. [56, 57]. At the outer event horizon, the action of the charged fermion becomes

$$S \simeq \int dt dr_* (\bar{\psi} (i \partial_t - e A_t) \gamma^t \psi - \bar{\psi} i \partial_{r_*} \gamma^{r_*} \psi), \quad A_t = -\frac{eQ}{r}. \quad (63)$$

Here we omit the contribution from angular components for simplicity, and  $Q$  is the charge of the black hole. In order to obtain the outgoing flow of the

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<sup>8</sup>From a different point of view, Eq. (2) would be meaningful since this operator contains running coupling  $y_N$ . Because this coupling depends on scale, the operator cannot be absorbed by fermion rotation in a covariant way.

energy at the future infinity, we usually impose the ingoing boundary condition for the current at the horizon. But since the above scalar potential diverges  $A_U \propto A_t/U$  at the horizon  $U = 0$  in the Kruskal coordinate, we need to take the gauge in which  $A_t = 0$  at the horizon (see discussions e.g. [56, 57])

$$A'_t = A_t + \partial_t \Lambda, \quad \Lambda = \frac{eQ}{r_H} t. \quad (64)$$

This shifts the energy level of the charged particles and the spectrum of the Hawking radiation is obtained by replacing  $\omega$  by  $\omega - \mu = eQ/r_H$ . Thus  $eQ/r_H$  indeed plays the role of the chemical potential in the thermal radiation.

The same procedure is applicable to the current setup. In our case, the “gauge transformation” to regularize the action at the horizon in the Kruskal coordinate is given by

$$\psi \rightarrow \exp \left( i \frac{C}{M_*^4} \partial_t (\mathcal{R}_{\mu\nu\rho\sigma} \mathcal{R}^{\mu\nu\rho\sigma}) \Big|_{r=r_H} t \right) \psi. \quad (65)$$

Thus

$$\mu = \frac{C}{M_*^4} \partial_t (\mathcal{R}_{\alpha\beta\gamma\delta} \mathcal{R}^{\alpha\beta\gamma\delta}) \Big|_{r=r_H} \quad (66)$$

becomes the chemical potential to describe the thermal radiation from the PBH.

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